ORIGINAL ARTICLE

An in-depth analysis of tool wear mechanisms and surface integrity during high-speed hard turning of AISI D2 steel via novel inserts

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Abstract

Over the years, machinists have been exploring the hard part turning of AISI D2 steels. Initially, cylindrical grinding was used for this purpose, but it was later replaced by single-point turning due to its advantages such as high material removal, low cost, and greater flexibility. Conventional inserts are used in single-point turning, but they have been reported to have large radial forces, high notch wear, and poor surface finish. Therefore, multi-radii wiper inserts were designed to overcome these machining issues, but their use was restricted to shallower depths of cut and moderate feed rates because of the thick chips produced by the high entry angle. Prime inserts, on the other hand, were designed with a modest entry angle, making them ideal for evaluating tool wear/life, material removal and surface roughness at greater cutting speeds, depths of cut, and feed rates. It was observed that cutting speed has a significant effect on tool wear/life with a contribution of 55.38% followed by feed rate (13.72%) and depth of cut (11.43%). Cutting speed (84.87%) and feed rate (13.01%) are observed to be the most significant parameters controlling material removed. It was also observed that feed rate has a significant effect on workpiece surface roughness with a contribution of 67.30% followed by depth of cut (20.60%), whereas cutting speed had no significant effect on surface roughness. Moreover, it is found that prime insert outperformed wiper and conventional inserts in terms of tool life/wear and surface roughness.

Keywords Hard turning · D2 steel · Prime inserts · Tool wear · Material removal · Surface roughness

1 Introduction

Hard turning has several benefits over cylindrical grinding such as reduced cutting time, high material removal rate, and greater flexibility; therefore, the former process is considered a better substitute finishing process than the latter [1]. Moreover, the fatigue life of hard-turned processed surfaces is almost double the corresponding ground surfaces' life [2]. These benefits make the hard turning an attractive alternative machining process compared to

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grinding, precisely in the automotive and die and mold manufacturing sectors [3]. The hard turning process is executed in dry mode; therefore, it is considered harmless in terms of environmental contamination thus saving the cost of cutting fluid, which in some cases accounts for 17% of the total machining cost [4]. In hard part turning, single-point tools are typically employed for machining steel and cast iron workpieces with hardness in the range of 45–65 HRC [5]. AISI D2 steel containing vanadium (V) and molybdenum (Mo) is a variant of tool steel with high contents of carbon (C) and chromium (Cr) as alloying elements [6]. Mechanical characteristics of AISI D2 steel after heat treatment can be improved such as good strength, high hardness, and enriched wear resistance [7]. AISI D2 steel is categorized as a difficult-to-cut material. The causes for this deprived machining are beyond its advantages as resisting materials. Numerous factors result in increased cutting tool wear: (i) extraordinary resistance retained at elevated temperatures, (ii) low thermal conductivity, (iii) exceptionally high amount of abrasive carbide particles inside the microstructure, and (iv) excessive chemical affinity. These issues are the key consideration in manufacturing industry for sustainable machining [8]. Therefore, selection of machining parameters and cutting inserts is a significant piece of the enigma.

Over the years, research studies concerning the turning of hard materials have grown in diverse ways. Previously, studies concentrated on the performance assessment of various tool materials specifically ceramics, PCBN, and coated carbides with prime attention on parametric evaluation [9–11]. Far along, the exertions moved to improve throughput echelons instead conceding the product quality. The idea of novel prime inserts (Fig. 1) was realized and their shape made it conceivable for higher feed rates along with the higher depth of cut in turning with better surface finish [8]. It has preferred the production facets of the machining overall. Seeing that the degree of interest might not be established for turning of difficult-to-cut materials [12], investigators have commenced precise examinations to explore the capabilities of the inserts for explicit circumstances [13–15]. The attentions

to estimating the factual ability of inserts in machining of difficult-to-cut material are nonetheless continued.

To physique the perspective, a survey of the pertinent literature on the turning of hardened materials is presented here. Liew et al. [4] optimized the machining cutting parameters in turning of AISI D2 steel using rhombic-D-type carbide inserts with 55° included angle as a cutting tool and nanofluid as a cutting fluid. They suggested a cutting speed (C_s) of 200 m/min for superior surface finish. For maximum tool life, 0.10 mm/rev feed rate (F_R) with $C_S = 100$ m/min was proposed as the optimal parametric combination. Khan et al. [17] used the mixed alumina ceramic tool for machining the glass fiber–reinforced plastic (GFRP) composite material and AISI D2 steel. They adopted the fixed 0.20 mm depth of cut (D_{OC}) and feed rate (F_R) of 0.08 mm/rev, while the C_S was within limits of 129–400 m/min. They found that flank wear was increasing as the cutting speed increased. Sirtuli et al. [18] examined an adhered film formed on squared PCBN inserts while machining of AISI D2 at $D_{OC} = 0.02$ mm, $F_R = 0.08$ mm/rev, and $C_S = 150$ m/min. They found that adhered film was not effortlessly splintered and persisted secure on the rake side like a shielding film. In another work, Guddat et al. [19] observed the performance of PCBN wiper inserts (nose radius: 0.4, 0.8, and 1.2 mm) during the turning of AISI 52,100 steel. They reported $R_a = 0.5$ μm at PCBN wiper insert nose radius = 1.2 mm and at $F_R = 0.30$ mm/rev. Dosbaeva et al. [20] evaluated the effectiveness of squared PCBN and coated carbide inserts for machining D2 tool steel at a constant $F_R = 0.10$ mm/rev and $D_{OC} = 0.06$ mm, while C_S varied at 60, 100, and 175 m/min. They observed that the coated carbide inserts outstripped costly PCBN tooling because of the development of lubricious tribo-layer at the rake side of the insert. Khan et al. [13] examined the high feed turning of AISI D2 tool steel with C-type-rhombic insert of different nose radii (0.4, 0.8, 1.2 mm). They observed that wear progressions were smooth for 0.4- and 0.8-mm nose radius inserts, while fracture occurred at the insert having a nose radius of 1.2 mm and at a high feed rate of 0.562 mm/rev. It was also reported in their study that almost 59% reduction in tooling
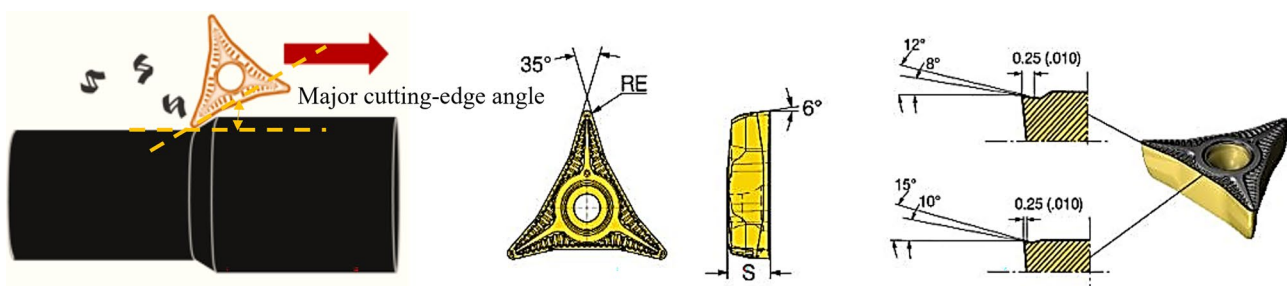

Fig. 1 Insert A-type (view of basic major cutting edge angle) [8, 16]

life and nearly 62% more material removal attained at high combination of nose radius and feed rate. Boing et al. [21] studied two distinctive configurations of square cemented carbide inserts: (i) grade 1105 and (ii) grade 4315, at fixed $F_R = 0.08$ mm/rev, $C_S = 150$ m/min, and $D_{OC} = 0.20$ mm. Tool lives of 10 min (with grade 1105) and 17 min (with grade 4315) were recorded based on the 200-µm flank wear criteria. Rajbongshi et al. [22] investigated the machining attributes for AISI D2 using textured and non-textured coated carbide tools. They found that 46% flank wear declined and 9% R_a reduced with textured tooling than the unfeatured. Anwar et al. [23] investigated the machinability of Ti-48Al-2Cr-2Nb (HV30 = 394.7) by using multi-coated (TiAlN/Al2O3/ZrCN) and plain tungsten carbide C-type inserts. They reported that plain tungsten carbide inserts show superior performance due to their better thermal conductivity as compared to the coated inserts while machining the heat-resistant Ti-48Al-2Cr-2Nb alloy.

In the case of high-speed turning of hardened materials through different inserts, various research findings have been established by researchers. For instance, Chen et al. [24] attained a steadiness between surface integrity and machining efficiency in turning AD730 by PCBN insert at $C_S = 200$–250 m/min. Soo et al. [25] observed a 40% improvement in tool life in the machining of Inconel 718 through TiSiN-coated PCBN inserts than uncoated inserts at C_S of 200 m/min. Tian et al. [26] investigated the impact of ceramic (Si_3N_4) inserts in high-speed turning of Fe-based GH2132 HRSA with C_S up to 200 m/min. They perceived that with the rise in cutting temperature, cutting forces decreased progressively. Recently, Günay et al. [27] evaluated the tool life and machining performance of Nimonic 80A under various circumstances: air-cooling, dry, and oil spraying using coated carbide tools and inserts code of PCLNR 2525M12. They found that

a cutting speed of 60 m/min in oil spraying resulted in better tool life and surface integrity. Thakur et al. [28] examined the high-speed machining behavior of Inconel 718 using the tungsten carbide insert (K20) tool. They observed that a cutting speed of 55 m/min with a feed rate of 0.08 mm/rev resulted in better surface finish. Mostly, the C_S remains in the range of 60–90 m/min, which is half of the acquired with advanced substrates. Therefore, an approach to attain a decrease in the machining time is to be attentive to carbide tooling [8]. Under this perception, high feed turning is offered as a substitute for using high speed (C_S) to keep the tool wear and cutting forces low [29]. Wiper inserts (multi-tool tip radius) can be used with the objective of two times feed without compromising the surface roughness [30]. All these studies describe the objective of decreasing machining times in turning hardened materials through advanced tools such as PCBN, ceramic, and wiper inserts.

Literature assessment describes that to enhance the cutting effectiveness of hardened materials especially D2 steel, several approaches have been employed. For instance, the use of low-temperature minimum-quantity lubrication (MQL), nanofluids, and dry machining has been investigated [31]. Regarding the tool geometry perspective, most of the reported studies have utilized the rhombic, square, and triangular traditional inserts, while investigators also concentrated on the capability of wiper inserts. However, few characteristic restrictions are associated with these configurations of inserts. The vital difficulty associated with rhombic and triangular insert types is notch wear incidence at higher feed rates. At the same time, the larger uncut chip thickness is related to the rhombic insert due to the larger approach angle, which in turn leads to more significant mechanical loading on the cutting tool. Even though square inserts exhibit less tendency to the formation of notch wear,

Table 1 Chemical composition and mechanical, physical, and thermal properties of D2 steel [34]

D2 steel composition		D2 steel properties					
Element	%	Mechanical			Physical and thermal		
		Name	Unit	Value	Name	Unit	Value
C	1.7	Poisson's ratio		0.27–0.30	Melting point	°C	1421
Cr	12.5	Elastic modulus	GPa	190–210	Density	kg/m³	7.7 × 1000
Mn	0.33	Impact strength	J	77	Thermal expansion	Per °C	10.4 × 10⁻⁶
Si	0.56	Compressive strength	GPa	2.76	Specific gravity		7.75
Mo	0.43	Hardness	HV	610–620	Machinability		55% to 65% of a 1% carbon steel
Ni	0.14						
V	0.90						
Co	0.50						
Fe	balance						

Table 2 Main aspects of A-type insert

Insert type	Inscribed circle diameter	Insert thickness	Nose radius	Major cutting edge angle	Positive clearance	Maximum allowed cutting depth
A	11 mm	6 mm	0.80 mm	27.5º	6º	1.5 mm

the issue of ease of access confines its use in precise parts [32]. Wiper inserts show the benefit of employing higher feed rates and improved surface roughness. However, low depth of cut (< 0.30 mm) and cutting speed limit their usage due to the reduced material removal rate [13, 33].

In contrast, excellent ease of access, less tendency to notch wear formation, uniform chip thickness, and inferior radial forces are the specified pros of the prime inserts [8]. From the viewpoint of machining hardened materials under aggressive cutting parameters, prime inserts might be better candidates for sustainable machining. Due to their novel shape, prime inserts could offer various advantages in hard turning, including the possibility of employing a higher depth of cut, feed rate, cutting speed, and hence, productivity. Prime inserts offer the lowest major cutting edge angle among all the inserts, which in turn reduce the uncut chip thickness and provide the possibility for an increase in productivity. Previously, limited work is reported on the use the prime inserts for hard turning. Therefore, it is worth investigating the true potential of the prime inserts for possible productivity improvement in hard turning. This work will employ the prime inserts for the hard turning of D2 steel with a wide range of turning parameters. The performance of the prime inserts will be compared with the conventional inserts.

2 Experimental work

Two bars of D2 tool steel formed by cold working with dimensions of 210 mm in length and 100 mm in diameter were used as workpiece material. Spark emission spectroscopy was performed to confirm the chemical composition of the workpiece material. The chemical composition is provided as per manufacturer's sheet which was further reverified through spectroscopical analysis. The obtained chemical composition (provided in Table 1) was in between the

recommended range of the material. The workpiece material bars were heat treated to a hardness of 610 HV.

Recently, high feed turning was suggested as a substitute for common turning process [8]. One vital aspect of high feed turning is that the tool is engaged with the workpiece in Fig. 1, with high feed rate and major cutting edge angle (27.5°), thus using a very small portion of the tool radius. Under prime inserts, two types of variants are manufactured by the tool manufacturers [16]: A-type, with three 35° vertices (corner angle) for light roughing, finishing, and profiling operations, and B-type, with resistant vertices (80°) for roughing. In this work, the performance of A-type prime inserts was explored because of their flexibility. A-type insert of ISO code CP-A1108-L5W, grade 4325, substrate HC, and coating CVD $TiCN + Al_2O_3 + TiN$ has been selected; its main aspects are given in Table 2. These prime inserts were attached to a tool holder with an ISO designation of CP-30AR-2020–11. The tool holder provides a rake angle of 0°.

Turning experiments were performed by a precision lathe (Emcomat 17-D) under dry environment as suggested for hard turning practice. To estimate the throughput advantages and assess the complete capabilities of A-type prime insert, experiments were piloted at higher values of C_S, D_{OC}, and F_R. The ranges of C_S and F_R were cautiously selected from the literature on the turning of D2 steel [13, 18, 20] to target the performance with the current tooling, while the D_{OC} values were chosen as per the manufacturer's recommendation [35, 36]. The levels of the selected three input variables are

Table 3 Levels of input variables

Levels	Input variables		
	C_S (m/min)	F_R (mm/rev)	D_{OC} (mm)
1	125	0.225	0.45
2	175	0.337	0.90
3	225	-	-

Table 4 Experimental array as per full factorial design

Test no	C_S (m/min)	F_R (mm/rev)	D_{OC} (mm)
1	175	0.225	0.45
2	225	0.225	0.45
3	125	0.225	0.90
4	175	0.225	0.90
5	225	0.225	0.90
6	125	0.225	0.45
7	125	0.337	0.90
8	125	0.337	0.90
9	175	0.337	0.45
10	175	0.337	0.90
11	225	0.337	0.45
12	225	0.337	0.45

Fig. 2 Experimental illustration: **a** turning of workpiece, **b** cutting tool and prime insert, **c** cutting zone
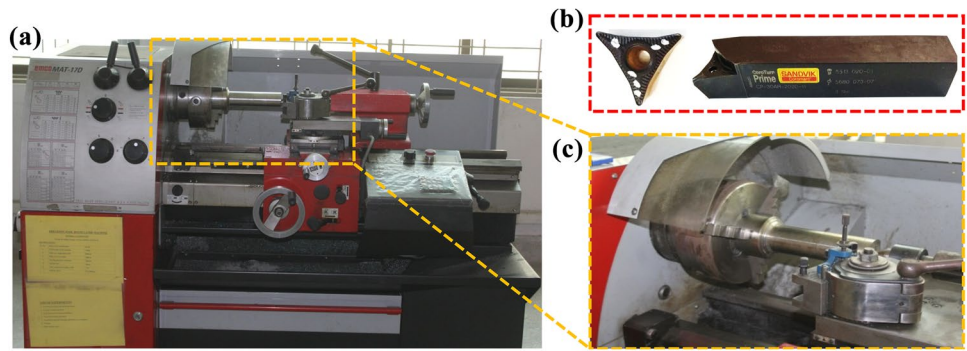
provided in Table 3. A full factorial design experimental design involving 12 tests was selected, as given in Table 4. The performance evaluation was accomplished by investigating the tool wear/life, surface roughness, and total material removal. Figure 2 demonstrates the experimental illustration: turned workpiece, cutting tool and prime insert, and cutting zone.

A coordinate measuring machine (CMM, model: CMM-CE450DV) was used to measure the tool flank wear for examining the tool life. ISO 3685 standard [35] was considered for taking the readings of tool wear, and termination of the test was based on either the tool wear reaching maximum flank wear (VB_B max.) of 200 µm or the tool was disastrously ruptured. Another point of limiting the wear criterion at the 200-µm level is to avoid unwarranted white layer formation on the workpiece surface because of the raised temperature during machining under the excessive flank wear. Throughout experimentations, images of worn tools were captured by a camera (available with CMM) having a magnification of $70\times$, while the surface texture meter of Taylor Hobson model no. SURTRONIC S128 was used to measure the surface roughness [37]. The cut-off length was selected as 0.8 mm with an evaluation length equivalent to 4 mm. The bar was indexed at four locations for surface roughness measurements, and the average value is reported. In-depth surface integrity assessment was executed only for the experiments that yielded maximum tool life (test 6), minimum surface roughness (test 2), maximum material removal

(test 3), and where most aggressive cutting conditions were applied (test 7). Workpieces' surfaces machined with both new and worn tools were examined under the SEM (JOEL 6060) conditions. Table 5 details the experimental runs for surface integrity assessment. A Mitutoyo micro-hardness tester (HM 124) was employed to quantify the micro-hardness of the cutting samples for 10 s dwell time with a load of 50 g, as per recommendation in [2, 21]. The micro-hardness is used to highlight the gradient of the heat-affected zone during machining. Therefore, the workpiece was cross-sectioned, and the micro-hardness was measured at a constant progressive distance to map the heat effects during turning. To present the changes, the micro-hardness was measured at the surface and progressed towards the center. In this context, the direction of micro-hardness is defined. A similar measurement methodology is established in literature on the turning process [1]. Testing equipment information is given in Table 6.

3 Results and discussion

3.1 Tool life/wear mechanism analysis and material removed

Flank wear progression vs machining time is shown in Fig. 3. Pattern shift in the flank wear curves is quite evident from mild to steep with the increase in the severity of operating parametric condition. Maximum tool life

Table 5 Test array for workpiece surface integrity assessment

Test code	C_S (m/min)	F_R (mm/rev)	D_{OC} (mm)	Tool condition	Machining length (mm)
2′	225	0.225	0.45	New	20
	225	0.225	0.45	Worn	
3′	125	0.225	0.90	New	
	125	0.225	0.90	Worn	
6′	125	0.225	0.45	New	
	125	0.225	0.45	Worn	
7′	225	0.337	0.90	New	
	225	0.337	0.90	Worn	

Table 6 Testing equipment information

Precision lathe (Emcomat 17-D)	
Motor	7.1 horsepower
Speed range	55–2350 rev/min
2 axes movement	Precisely up to 0.001 mm
Slide-way range (longitudinal)	800 mm
Crossway slide range	200 mm
Feed longitudinal range	0.045–0.787 mm/rev
Cross-feed range	0.023–0.406 mm/rev
Coordinate measuring machine (CMM, model; CMM-CE450DV)	
Measuring travel	$400 \times 450 \times 250$ mm (X, Y, Z)
Resolution	Renishaw linear scales 0.001 mm
Operation	Manual
Transmission	Linear guideway and drive nut
Accuracy	U1 = 2 + L/200 um; U3 = 4 + L/100 μm (temperature 20 °C ± 1), humidity: 55 ~ 65%
Granite plates	DIN. 876, 0 grade (area 590×850 mm)
Machine dimensions	$92 \times 97 \times 204$ cm (including stand frame)
Surface texture meter (Taylor Hobson model no. SURTRONIC-S128)	
Measuring parameters	Ra, Rz, Rt
Range	400 μm
Resolution	50 nm
Sampling travel	0.25–25 mm
Storage temperature	0 to 50 °C
Storage humidity	Humidity 0 to 80% non-condensing
Battery life	2000 measurements
Micro-hardness tester (Mitutoyo HM-124)	
Standard	ISO 6507–2, ISO 4545–2, JIS B 7725
Resolution	0.1 μm
Measuring travel	25×25 mm
Test force range	0.05 g to 2.0 kg

of ~19 min was recorded in test 6 conducted at the lowest cutting speed (125 m/min), feed (0.225 mm/rev), and depth of cut (0.45 mm) combination, while keeping the cutting speed at the minimum level (125 m/min) and either increasing the feed rate or depth of cut to next level, i.e., 0.337 mm/rev feed rate, 0.90 mm depth of cut, produced 47% drop in tool life (tests 7 and 3). Contrarily, keeping the feed rate (0.225 mm/rev) and depth of cut (0.45 mm) at the minimum level and escalating the cutting speed from 125 to 175 m/min caused ~54% decrease in tool life, with a value of 8.62 min, reported in test 1. Tool life was less than 5 min in all other tests where any of the two cutting parameters were at their maximum level. One-to-one comparison is not possible; however, still the results of this work are compared with the previous literature. When compared with the wiper inserts evaluated in [32] for turning the D2 steel at 125 m/min, 0.0281 mm/rev feed rate, and 0.20 mm depth of cut, ~58% higher tool life is obtained in test 6 of this work. Tool life in Ref. [33] with wiper insert was 12 min at 140 m/min

cutting speed, 0.225 mm/rev feed rate, and 0.20 mm depth of cut, which is 36% lower in comparison to the current work. In comparison to PCBN tools evaluated at $C_s = 170$ m/min, $F_R = 0.15$ mm/rev, and $D_{OC} = 0.30$ mm, tool wear was reported to be 275 μm after 7 min of cutting. This value of tool wear is 38% higher when compared with the test 1 of the current after the same machining time.

It is important to highlight that wiper insert applications are limited to finishing applications with a depth of cut range of 0.10–0.20 mm [13, 33]. However, with the current modified prime tooling, the depth of cut range is extended to 0.90 mm. Therefore, in terms of depth of cut, the performance of prime tooling is superior to wiper tooling. Even with ceramic wiper tooling, the window of cutting speed cannot be pushed beyond 150 m/min [33]. Moreover, with novel excel inserts, the cutting speed was restricted to 100 m/min [32]. Although a cutting speed up to 180 m/min was reported with conventional carbide tooling [38], the instance of fracture was evident. With this prime tooling,

**Fig. 3** The progression of flank wear with respect to cutting time
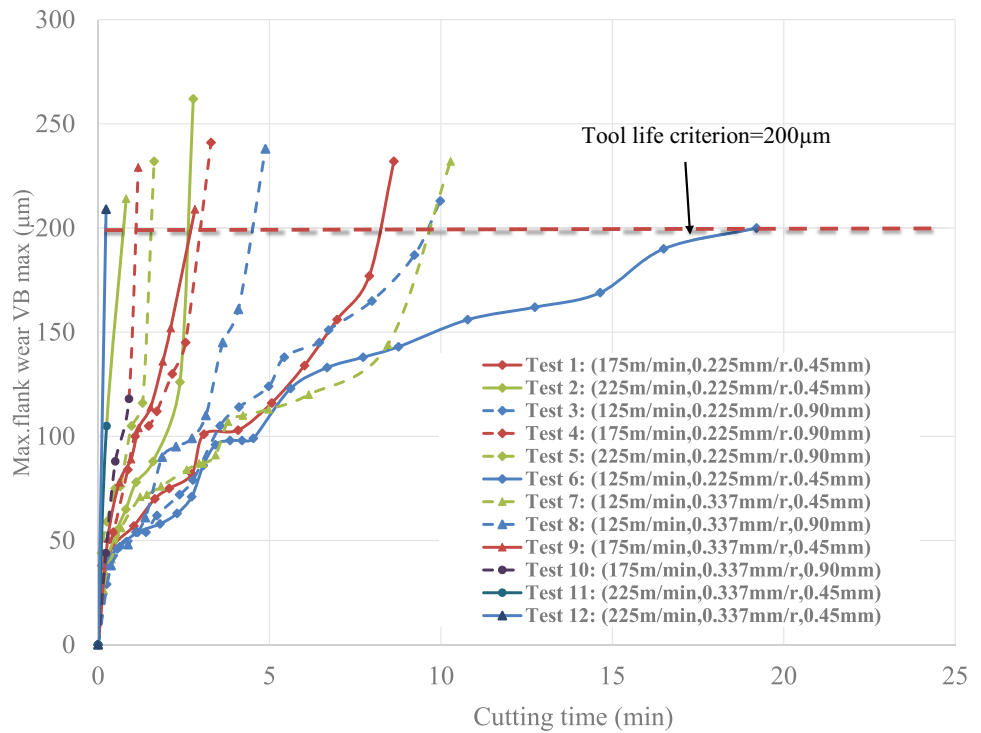
tool life of approximately 9 min was recorded at a cutting speed of 175 m/min, feed rate of 0.225 mm/rev, and 0.45 mm depth of cut with relatively uniform tool wear progression. This indicates the superiority of these inserts over wiper, conventional, and excel tooling.

In general, a test conducted at 225 m/min cutting speed resulted in the occurrence of fracture indicating the cutting speed regime unsuitability for the current prime insert. The maximum cutting speed compromised the tool life significantly with a value of less than 3 min for all trials conducted at 225 m/min. Contrarily, in all other trials, tool wear was relatively uniform. Minimum tool life of less than a minute was obtained in test 12, conducted under harsh cutting conditions.

The main effects of tool life are shown in Fig. 4. Not surprisingly, increases in cutting speed, feed rate, and depth of cut lead to reduction in the said response. An increase in cutting speed produces a rise in temperature which ultimately intensifies the tool wear. Increases in feed rate and depth of cut lead to greater chip cross-sectional area which in turn cause higher mechanical loading on the cutting tool, hence resulting in a lower tool life. Similar results in terms of feed rate/depth of cut increase were reported by Khan et al. [33] while using wiper inserts for hard turning of D2 steel. ANOVA calculations in Table 7 highlight that all factors are significant with cutting speed capturing maximum PCR of 55.38%, depth of cut of 11.43%, and feed rate of 13.72%.

The prime tooling wear progression is shown in Fig. 5. Tool wear was relatively uniform for the trials performed at a cutting speed of 125 m/min as shown in test 6; however, in some tests conducted at this speed, a fracture was noticed at test cessation. Fracture at the tool nose was encountered in the majority of the tests completed at 225 m/min with meager tool life such as tests 5, 7, and 11. The SEM micrographs of test 6 and test 7 are shown in Fig. 6 to further analyze tool wear mechanism.
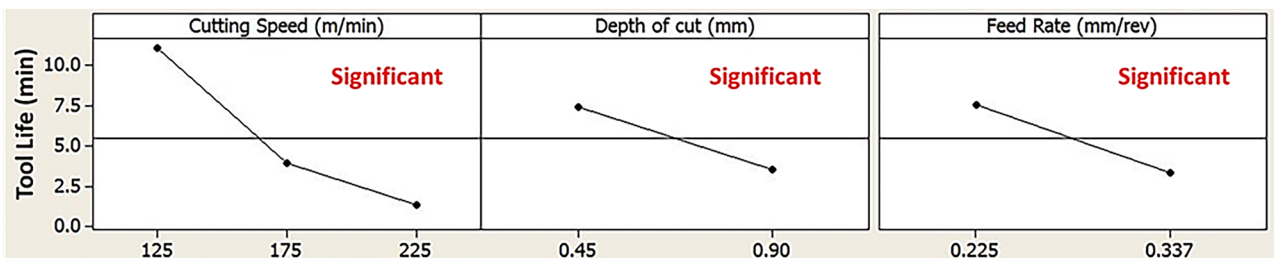
Fig. 4 Plots for main effects of tool life

Table 7 ANOVA for tool life

Source	DF	Seq SS	Adj MS	F value	P value	PCR (%)
C_S	2	202.375	101.87	16.66	0.002	55.38
D_{OC}	1	45.357	45.357	7.47	0.029	11.43
F_R	1	53.214	53.214	8.76	0.021	13.72
Error	7	42.517	6.074			19.47
Total	11	343.464				
R-Sq(adj) = 80.55%						

Material removed against tool life for each experimental test is presented in Fig. 7. Maximum of 252.6 cm^3 of material was turned against 9.98 min tool life for test 3, while minimum material removed was recorded as 16.38 cm^3 against test 7 with 0.23 min tool life. High depth of cut results in greater material removal but also compromises tool life. For example, test 7 produces near equal material removal to test 12 but shows ~50% low tool life. The material removed achieved through prime technology tooling is prominently higher than that reported in literature. The maximum material removal of 252.6 cm^3 with a tool life of 9.98 min in test 3 using a novel prime insert in current work is 56.26% higher than the material removal of 107.95 cm^3 of D2 steel using wiper ceramics insert having a nose radius of 0.8 mm at a feed rate of 0.225 mm/rev reported by Khan et al. [13], while the material removal in test 3 is 42.17% higher than that in Khan et al. [33], who observed material removal of 146.06 cm^3 of D2 steel using wiper insert at a moderate feed rate of 0.281 mm/rev. Dosbaeva et al. [20] reported MRR (1.05 cm^3/min) with tool life of ~8 min at flank wear of 0.2-mm criteria for PCBN inserts using C_S = 175 m/min, which is significantly lower in comparison to test 1 of current research.

Analysis of variance outcomes of material removed are provided in Table 8. Cutting speed (84.87%) and feed rate (13.01%) are observed to be the most significant parameters controlling material removed. To aim for sustainable machining, the reliability and use of processing resources should be properly managed, ensured, and implemented [31]. The aggressive conditions (roughing) result low energy consumption, reduced labor cost and high control over production cycle time. Also, the sustainable machining goal will be supported through prime technology tooling.

3.2 Work surface roughness

The variations of surface roughness on the basis of flank wear criteria (flank wear ≥ 200 μm) are presented in Fig. 8. With new tooling, R_a values were generally lower (0.5 to 1.06 μm) for tests 1 to 6 (performed at the lowest level of feed rate at 0.225 mm/rev). However, approximately 1.5 to 2.5 times increase in workpiece surface roughness was observed when turned with the worn tooling with a maximum value of 1.54 μm in tests 1 and 5. For tests 7 to 12 conducted at the highest feed rate/depth of cut combination (0.337 mm/rev and 0.90 mm), R_a values were generally higher from 1.3 to 2.42 μm for new tooling while 1.44 to 2.16 μm for worn tooling. In tests 9, 10, and 11 where depth of cut is 0.45 mm, workpiece surface roughness values were generally lower than 2 μm. It is clear from Fig. 8 that R_a values were lower in the case of new tooling for tests 1 to 6 than the worn tooling when feed rate was low, while with high feed rate, the values of R_a were high for new tooling than the worn tooling. The surface roughness is highly dependent on the F_R and nose radius (r_n) of tool. The mechanics of turning operation influencing surface roughness is quantified in Eq. 1 [39]. In any scenario, at constant nose radius, the surface roughness value would rise at the rate of feed rate squared, demonstrating that feed rate not only has a significant impact on surface roughness, but also can overwhelm the effects of other factors at high levels [13].

$$R_a \approx \frac{F_R^2}{32 r_n} \tag{1}$$

In comparison with current work on surface roughness evaluation of Ref. [40], minimum R_a values were observed to be approximately 0.80 μm for D2 steel using CVD-coated carbide insert under aerosol MQL machining that is ~60% higher than roughness of 0.5 μm obtained in this work. Similarly, Rajbongshi et al. [22] obtained roughness of around 1 μm while turning D2 steel with a textured tool, which again is higher than that achieved in the current work. With the intensification in D_{OC} or F_R, surface roughness rises by ~70–80%. At C_S = 225 m/min, F_R = 0.225 mm/rev, and D_{OC} = 0.45 mm, surface roughness with new tool was recorded to be R_a = 0.52 μm and went up to R_a = 1.24 μm with worn tooling. Sharma et al. [41] evaluated nanofluids and resulted in around 2 μm surface roughness at a feed rate of 0.20 mm/rev, which is high compared to the aggressive conditions investigated in this study. Another study on the machinability of AISI D2 steel using PCBN insert [42] achieved R_a = 1.9 μm post ~7 min of turning. However, this roughness is around ~100% higher than that obtained in this research for test 2 (225 m/min, F_R = 0.225 mm/rev, and D_{OC} = 0.45 mm).
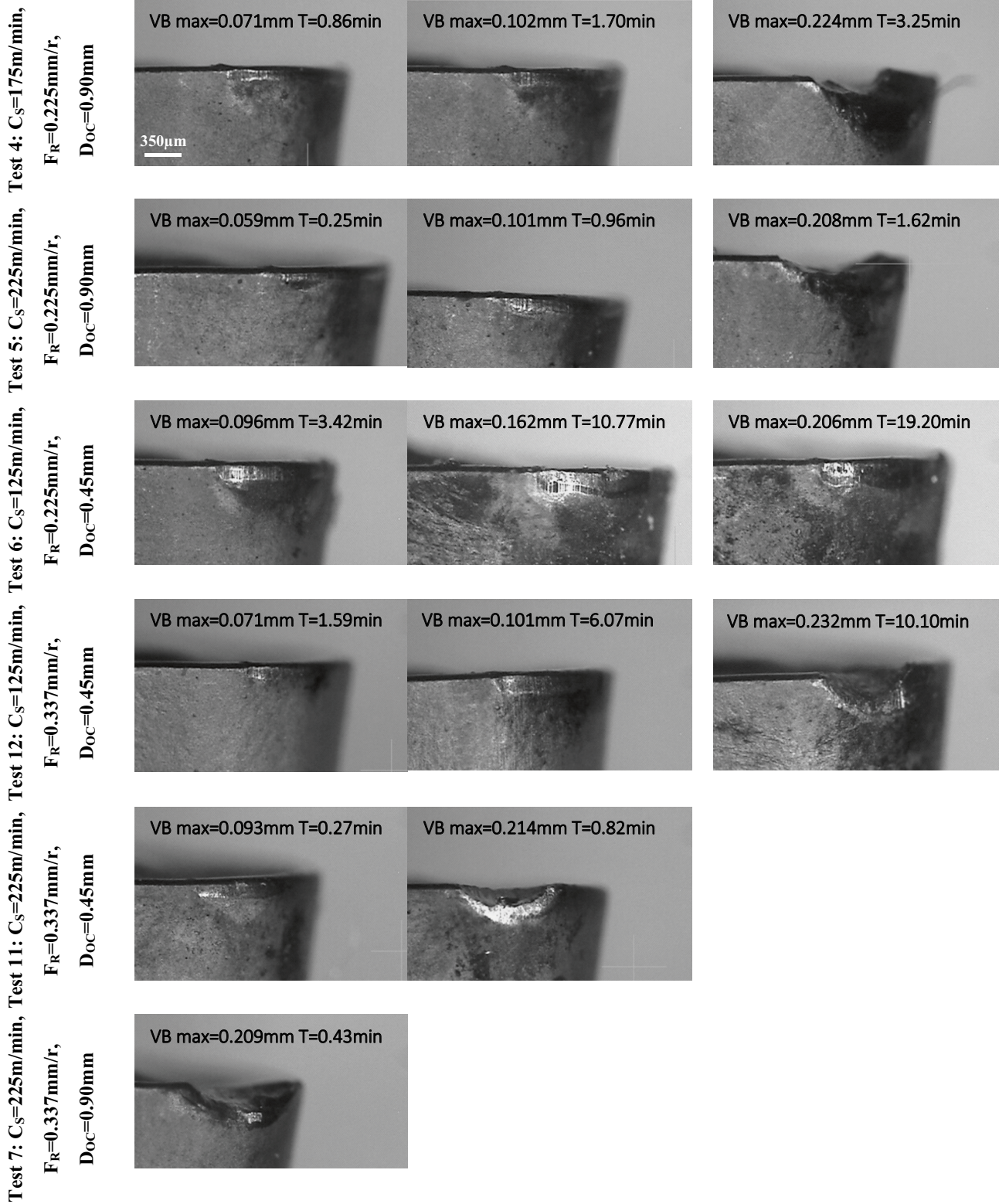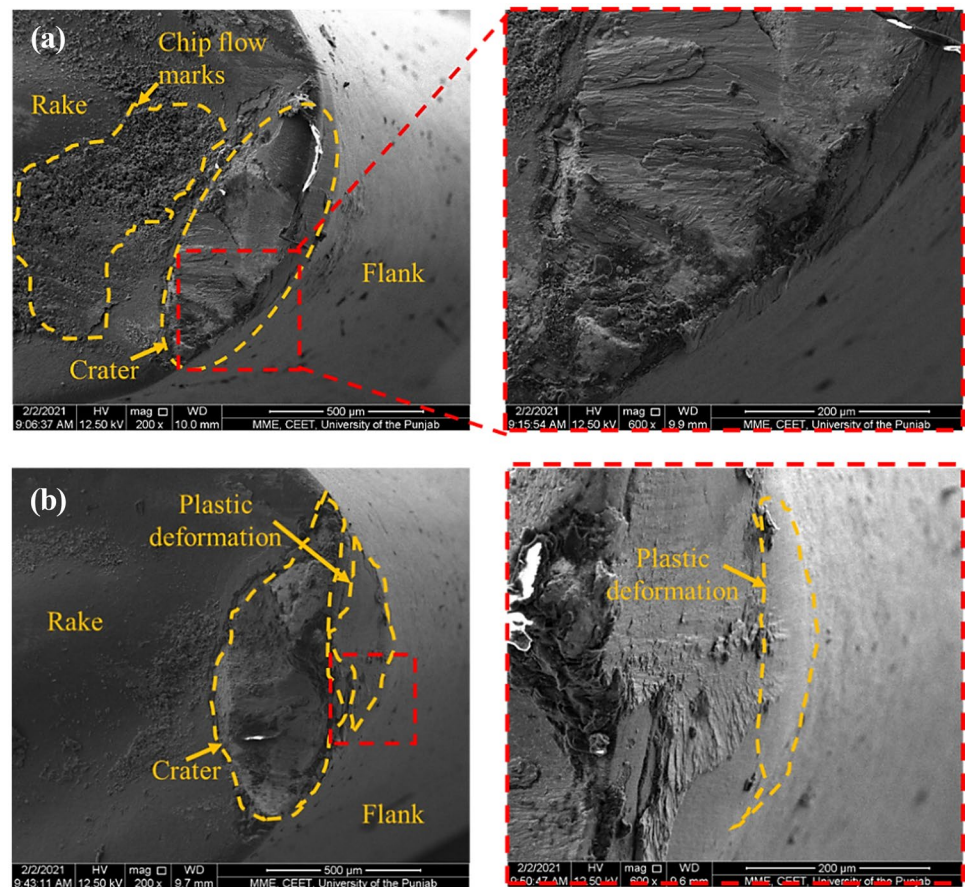
Fig. 5 Tool wear progression

Fig. 6 SEM micrographs of inserts: **a** test 7 at $C_S = 225$ m/min, $F_R = 0.337$ mm/rev, and $D_{OC} = 0.90$ mm, **b** test 6 at $C_S = 125$ m/min, $F_R = 0.225$ mm/rev, and $D_{OC} = 0.45$ mm

The trend plot of surface roughness for both tooling conditions is shown in Fig. 9. It can be observed that increases in feed rate and depth of cut lead to an increase in surface roughness. The increased cusps height of the machined surface, which would result in a poor surface finish, is related to the increase in R_a with feed rate [13]. However, an increase in cutting speed from 125 to 225 m/min resulted in a decrease in surface roughness in the case of new tooling; the same trend has been reported by Amigo et al. [8]. However, in the case of worn tooling, the values of surface roughness vary with an increase in cutting speed as depicted in Fig. 9. It is evident that D_{OC} (67.30%) and F_R (20.60%) influence surface roughness significantly (see Fig. 9a and Table 9) in the case of new tooling. However, in the context of worn tooling, feed rate effect (52.68%) on roughness increases significantly as compared to depth of cut (14.97%) (Fig. 9b and Table 9).

As evident from Table 9 for new and worn tooling, analysis of variance showed that except cutting speed, both variables showed significant control over surface roughness regardless of tool wear. For new tool, depth of cut was more dominant, while for the worn tooling, feed rate influenced remarkably.

3.3 Micro-hardness and microstructural evaluation

Micro-hardness profile for subsurface evaluation based on new and worn tool conditions has been carried out and its measurements are shown in Figs. 10 and 11, respectively. According to previous research [13, 33], the rubbing and plowing associated with worn tooling (flank wear ≥ 150 m) increased material deformation and elevated micro-hardness; thus, the micro-hardness of both new and worn tools was measured. Regardless of the input parameters or tool state, all subsurface micro-hardness profiles revealed that strain hardening is produced from 150- up to 300-μm depth. In the case of new tooling, maximum micro-hardness of 726 HV was recorded perpendicular to the feed direction for test 3 (Fig. 10), while for the worn tooling, the value of micro-hardness was 750 HV for test 3 which is higher than the new tooling (Fig. 11). A maximum micro-hardness value approximately 800 HV was measured for test 1 with worn tooling. An increasing trend is witnessed in micro-hardness against all parametric settings for worn tooling. Around ~22% increase is prominent with worn insert as compared to bulk material within the range of ~25 μm. Furthermore, due to stronger rubbing effects that the worn tool exerted on the machined surface, micro-hardness with the worn tooling was
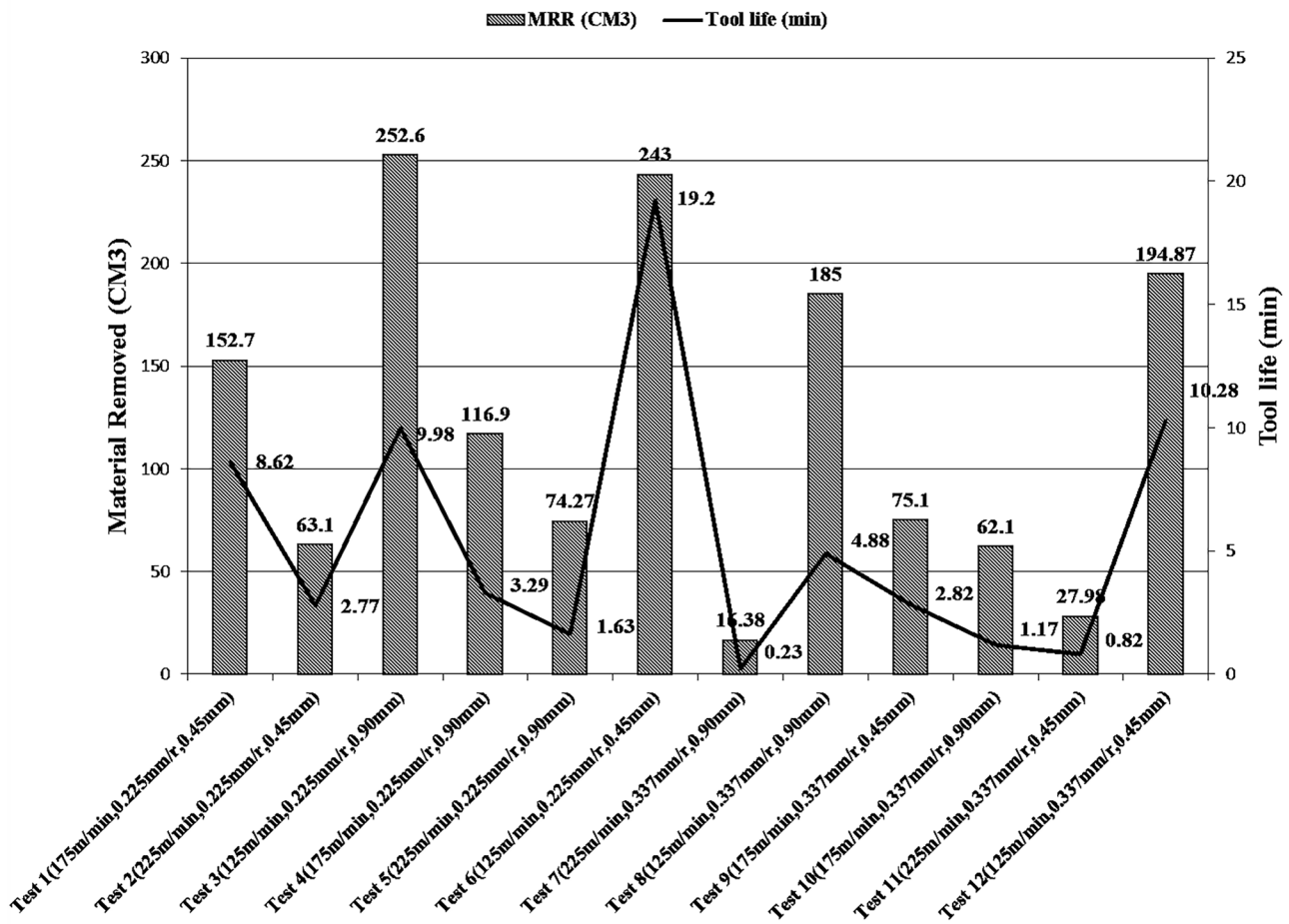
Fig. 7 Comparison of material removed and tool life

approximately 10% higher (on average) than with its new counterpart.

Initially, softening of material occurred beneath the machined surface irrespective of tooling conditions. Softening is accounted due to the high temperature produced because of the worn edges of the tool. At 10-μm depth, minimum values of 472 HV (for new tool) and 526 HV (for new tool) were obtained from the machined surface. The machined surface goes under the aging process because of the higher cutting temperature at the surface, and aging decreases surface hardening resulting in a decline

in micro-hardness [43]. As a result, it may be concluded that thermal softening caused by high temperatures in dry machining causes the D2 steel underlying the machined surface to soften.

Under various parametric conditions for both new and worn tooling, optical micrographs are shown in Fig. 12. In terms of microstructural damage, there was no evidence of a white layer, which is commonly thought to be a limiting factor for hard turning due to the risk of sudden failure of the machined surface [44]. No white layer is present ensuring the suitability of prime technology tooling. However, such layer is noticed in literature

Table 8 Analysis of variance for material removed

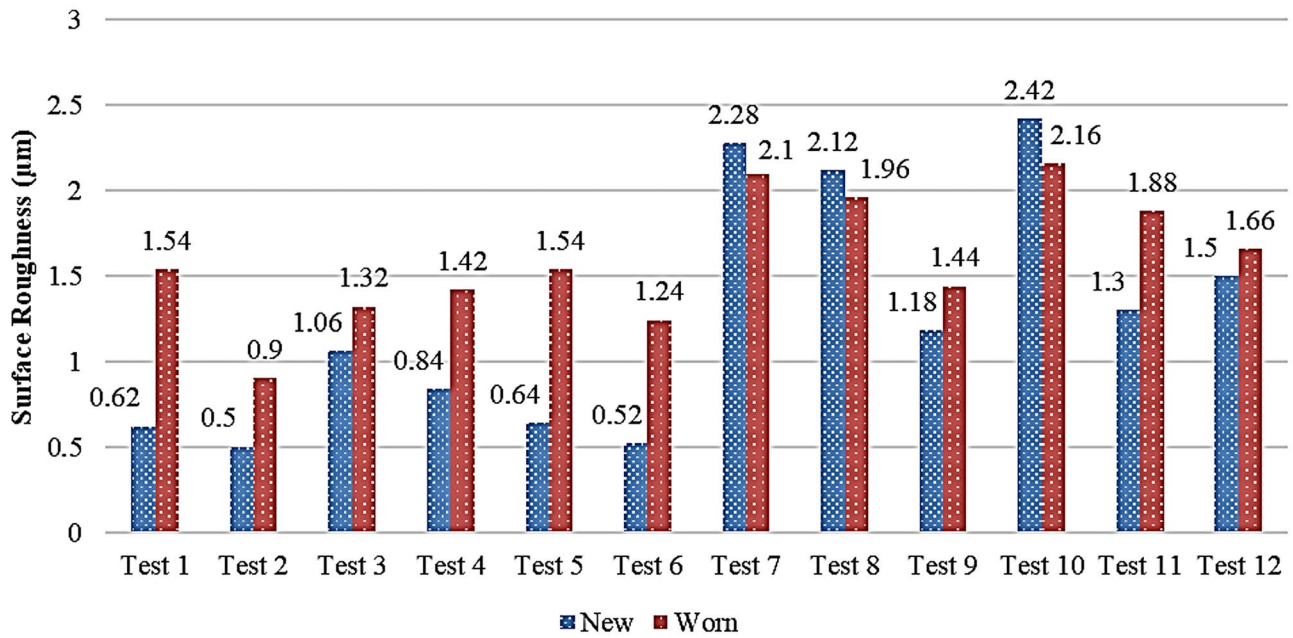| Source	DF	Seq SS	Adj MS	F value	P value	PCR (%)
C_S	2	62,632	31,316	232.9	0.000	84.87
D_{OC}	1	204	204	1.52	0.258	0.09
F_R	1	9698	9698	72.14	0.000	13.01
Error	7	941	134			2.03
Total	11	73,475				
R-Sq(adj)=80.55%						

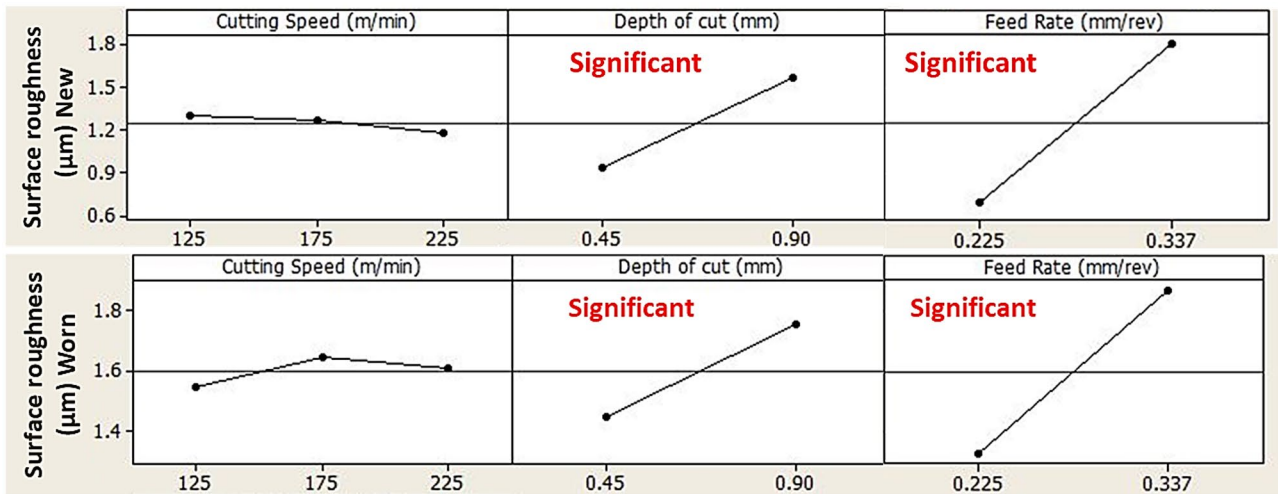**Fig. 8** Surface roughness of machined surface through new and worn tool conditions

Fig. 9 Trend plot of surface roughness of machined surface through (a) new tool conditions and (b) worn tool conditions

Table 9 Analysis of variance for surface roughness

Source	New tools		Worn tools	
	P value	PCR (%)	P value	PCR (%)
C_S	0.805	3.16	0.841	11.14
D_{OC}	0.004	20.60	0.052	14.97
F_R	0.000	67.30	0.005	53.68
Error		8.94		20.21

during the machining of D2 steel, which causes problems in flank wear [22]. The low magnitude and uniformity of flank wear are attributed to the absence of the white layer. The investigations of microstructure show the occurrences of material laps producing damage-free surface (in the case of new tool), while no significant deformed grain structure is evident in the case of new tools. However, a few defects such as plastic deformation, material pullout, and micro-crack traces are observed with worn tools.

Fig. 10 Micro-hardness profile for subsurface evaluation based on new tool conditions

Fig. 11 Micro-hardness profile for sub-surface evaluation based on worn tool conditions
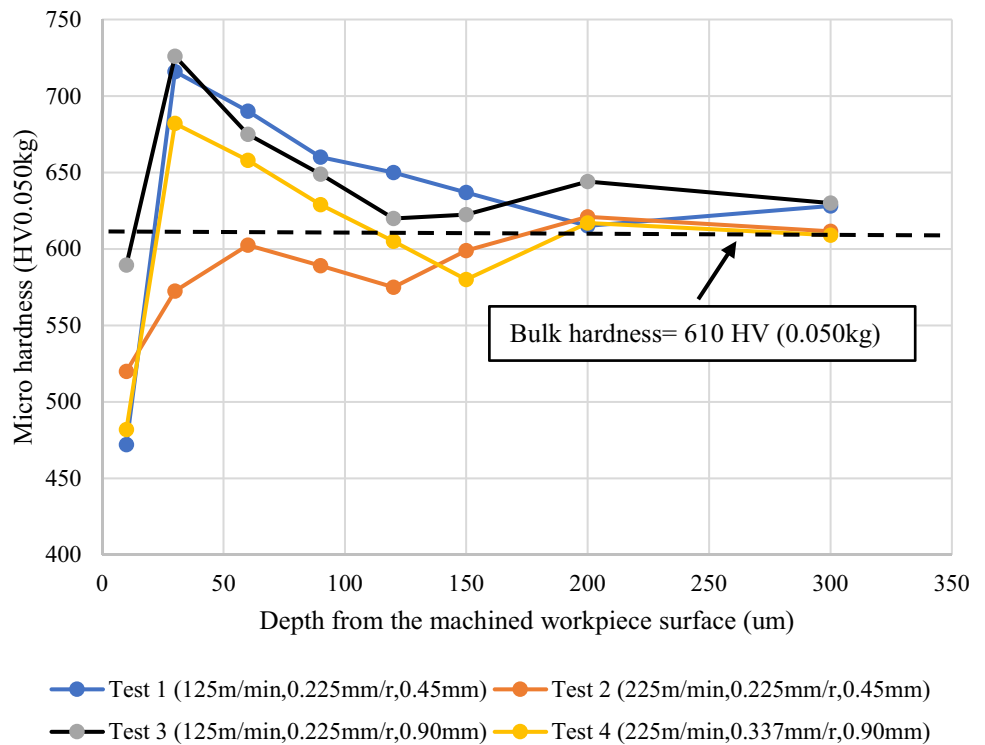
The material plucking leads to microstructural damage which further promotes material cracking. The minimum flank wear in the case of test 6 (C_S = 125 m/min, F_R = 0.225 mm/rev, and D_{OC} = 0.45 mm) ensures lower cutting forces and uniformity of the temperature at the surface showing minimum surface damage. Therefore, low feed rates, low cutting speed, and low depth of cut regime are recommended to avoid microstructural damage. At the same time, it is worthy to mention that other shape inserts used previously [32, 33] to machine D2 steel with the same level of turning parameters showed inferior performance as compared to the newly employed prime inserts.

Fig. 12 Optical micrographs show the cross-sectioned surfaces processed through new and worn tooling (**a**) test 2, (**b**) test 7, and (**c**) test 6

4 Conclusions

The research work investigates prime insert configuration with various cutting parameters (feed rate, cutting speed, and depth of cut) in turning of hardened material AISI D2 steel. A systematic study involving tool life/wear, material removal, and workpiece surface integrity assessment is carried out which is important in establishing economic justification for the usage of prime inserts. The following insights are drawn from thorough physical evidence such as microscopical, SEM, and statistical analyses.

1. The maximum tool wear is evident in the result of high values of D_{OC} (11.43% contribution) and F_R (13.72% contribution) through crater wear mechanism. Prime turning technology outperformed in terms of tool life and resulted ~19 min at the lowest processing conditions 125 m/min C_S (55.38% contribution), 0.225 mm/r, and 0.45 mm, as minimum value 200 μm flank wear criterion.

2. Cutting speed (84.87%) and feed rate (13.01%) are observed to be the most significant parameters controlling material removed. Maximum 252.6 cm^3 of material is removed against 9.98 min tool life for test 3 at $C_S = 125$ m/min, $F_R = 0.225$ mm/rev, and $D_{OC} = 0.90$ mm.

3. New tooling influences surface roughness through D_{OC} (67.30%) and F_R (20.60%) and worn tooling influences by feed rate (52.68%) and depth of cut (14.97%). For new tool, depth of cut was more dominant, and for worn tooling, feed rate influenced remarkably. The parametric setting $C_S = 225$ m/min, $F_R = 0.225$ mm/rev, and $D_{OC} = 0.45$ mm produced superior results in comparison to others.

4. Regardless of the input parameters or tool state, all subsurface micro-hardness profiles revealed that strain hardening is produced from 150- up to 300-μm depth. Around ~22% increase is prominent with worn insert as compared to bulk material within the range of ~25 μm.

5. In terms of microstructural damage, the low magnitude and uniformity of flank wear are attributed to the absence of the white layer. Moreover, no significant deformed grain structure is evident in the case of new tools.

This study investigates the tool wear mechanisms and surface integrity during high-speed hard turning of AISI D2 steel via novel inserts. There is an urgent need to isolate the minor chipping and critical wear mechanisms to present better control over it. Further extension of the work in the direction of the origin of wear mechanisms is recommended. Moreover, the correlation of the wear mechanisms with chip morphology could be investigated to further understand the origin of the mechanisms.

Author contribution Conceptualization: S.A.K. and M.F.A.; methodology: M.F.A., M.A.A., and M.U.F.; data curation: M.F.A.; writing – original draft preparation: M.A.A. and M.U.F.; writing – review and editing: M.A.A., M.U.F., S.A., and A.A.; project administration: S.A.K. and G.M.U.; funding acquisition: S.A. and A.A

Availability of data and material The necessary data used in the manuscript is already present.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All authors are agreed upon the current version of submission for publication.

Conflict of interest The authors declare no competing interests.

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